Using Horizontal Gradients to Interpret Central-Loop TDEM Data near Geological Contacts

EM3.4

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Summary

In areas of inhomogeneous geology interpretation of central-loop or coincident loop data can give misleading results. Although analysis of the horizontal component can provide diagnostic information on the inhomogeniety this field is seldom measured. An alternative to this field is the horizontal gradient of the vertical component. This quantity may be calculated from the vertical field data and may be used in much the same manner a the horizontal component data.

For a truncated sheet model, which can be a good approximation to surficial overburden, the horizontal gradient transients are peaks that decay exponentially at later times. When plotted as time profiles the horizontal gradients at early times are sharply peaked near the edge but at later times the plots are broader, smoother and peak further from the contact. The position and temporal characteristics of the transient and profile peaks are linearly related to the conductance of the surficial overburden. This latter quantity may be calculated from the apparent velocity of the transient or profile peak. The distance to the edge can be determined from the time constant of the late time decay. These characteristics are illustrated with a field example.

Introduction

TDEM data collected in the central-loop configuration has long been used in groundwater and mineral exploration, often with good success (Irvine and Staltari,1984). One-dimensional inversions of such data have provided good estimates of the vertical resistivity distributions except in areas of inhomogeneous geology and these areas are often evident from a cursory examination of the raw data. In many cases, however, the area of interest is also an area of discontinuous geology, and it is necessary to be able to recognize the signature of target bodies and be able to differentiate them from surface effects.

Previous studies have shown that central-loop horizontal fields provide useful and diagnostic information near geological contacts. (Wilt, and Becker, 1988, Wilt and Williams, 1989; Newman et al., 1988). Of the large number of existing central-loop soundings, however, only a small percentage have involved the measurement of the horizontal field component in addition to the vertical field. Actually, in most field surveys only the time derivative of the vertical field (voltage response) is measured. The result is that little of the analysis developed for the horizontal field has much application for these data. If a series of adjacent central loop soundings are collected as a profile, however, a psuedo-gradient of the field quantity may be constructed. This is made by taking the field difference between adjacent soundings at equivalent time windows and dividing by the station separation. This horizontal "gradient" will only be nonzero if there are lateral variations in conductivity in the profile direction. It should therefore be a useful quantity for interpreting these variations.

In this short paper we examine a single type of geological inhomogeneity, the discontinuous surficial overburden using the horizontal gradient of the central-loop voltage; a quantity that may be easily calculated from field data. With the aid of this simple model we first develop some interpretation techniques and then apply these methods to some field data.

Numerical Calculations using Program SHEET

Program SHEET is a FORTRAN code for calculating the vertical and horizontal field transient response over a conducting half-plane in air (Weidelt, 1983). The program calculates impulse-response vertical and horizontal magnetic fields within or exterior to a finite loop source situated over an arbitrarily dipping truncated sheet; it may also be used to calculate the coincident loop response that is used with the SIROTEM system (Buselli and O' Neill 1982). The program uses the Wiener-Hopf technique to calculate the response in the frequency domain and uses free-decay modal expansion (instead of Fourier transformation) to calculate the transient response from the harmonic results (Weidelt, 1983).

A flatlying truncated thin-sheet may be good approximation to a layer of discontinuous overburden. Such overburden has long been a troublesome problem in EM since its response can sometimes be confused with a steeply inclined ore deposit (Spies and Parker, 1984). We use program SHEET to calculate central-loop transient fields at various positions on the surface of the sheet and use this data to derive some simple techniques for determining the conductance of the sheet and the location of its edge. We found that at all but the earliest times the horizontal gradient data for the coincident loop and central loop configurations are interchangeable.

A plot of the horizontal gradient transient voltages at sites 250m, 400m and 700m inwards from the edge of a truncated layer of conductance S=10 is given in Figure 1. The transients all form positive peaks before decaying exponentially at late time. For stations closer to the edge the peaks are sharp and occur earlier in time; for stations further from the edge the peaks are broader, lower in amplitude and occur at later times. These plots are similar to the horizontal field voltage transients described by Dallal (1985). It was shown in Dallal (1985) and Wilt and Becker (1988) that the position of the peak in the horizontal field transient and its late time slope can be related to the sheet conductance. In a similar manner the same characteristics for the horizontal gradient of the vertical field transient may also be related to the contact parameters.

We found that for a truncated sheet the position of the horizontal gradient positive peak is a linear function of lag time. This is a similar result to the horizontal field analysis given in Wilt and Becker, (1988). The velocity of the gradient peak is slightly slower than the horizontal field transient peak; this quantity was empirically found to be

$$V_{tr} = \frac{\Delta x_{peak}}{\Delta t_{peak}} = \frac{1.5}{\mu_0 S} \qquad (1)$$

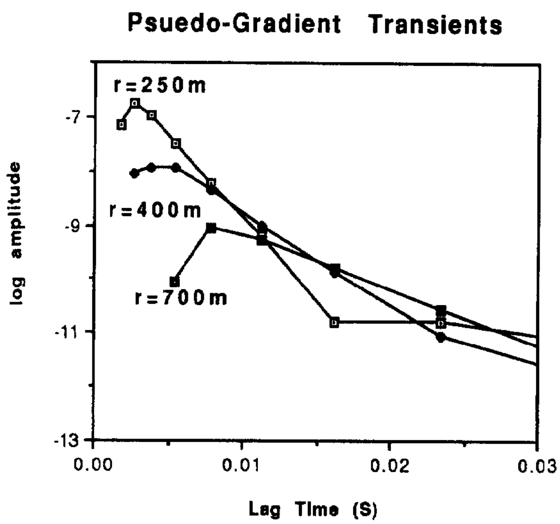

Figure 1 Horizontal gradient voltage transients 250, 400 and 700m from the edge of truncated sheet.

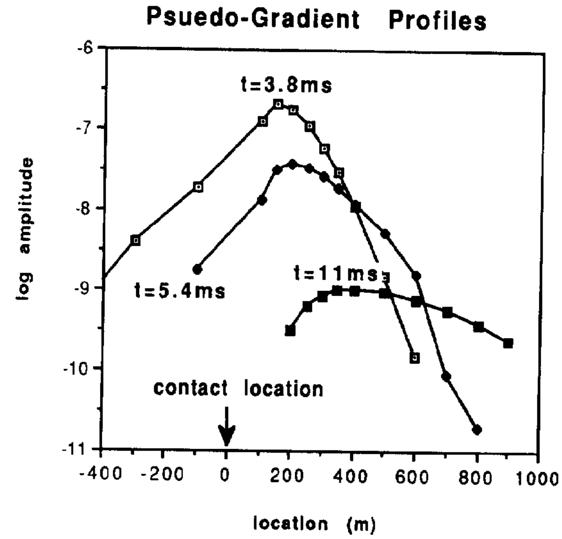

Figure 2 Horizontal gradient time profiles over a truncated sheet.

where S is the conductance of the truncated sheet, μ_0 is the free-space magnetic permeability and V is the velocity in m/s. Note that whereas the velocity of the horizontal field peak may be physically related to the movement of induced currents in the sheet this last relation is simply an empirical result. In a similar manner we have empirically found that the late-time slope of the horizontal gradient transient data can be fit to a function given by

$$\tau_1 = \frac{\tau}{\mu_0 S a} = 0.5((X/a)+1.0) \tag{2}$$

where tau is the measured time constant, X is the distance from the center of the loop to the edge and a is the loop radius. Note that this expression is only slightly different from those given for the horizontal field time constant in Wilt and Becker (1988). With a minimum of three soundings the above two expressions allow us to calculate the conductance of the truncated sheet and estimate the distance from a sounding point to the edge.

The horizontal gradients plotted as time profiles for a truncated sheet form a series of peaks that broaden, diminish in amplitude and are centered further from the edge with increasing lag time (Figure 2). We can plot the position and amplitude of these profile peaks against lag time for the gradient data much as was done for the horizontal fields in Wilt and Becker (1988) to determine sheet conductance and distance to the edge. The velocity of the gradient voltage peak is given by

$$V_{pf} = \frac{0.4}{\mu_0 S} \tag{3}$$

If the amplitude of the horizontal gradient profile peaks against is plotted against normalized time,

$$t_n = \frac{t}{\mu_0 S a}$$

the plots for all truncated sheet models collapse into a single curve. This master curve, shown in Figure 3, is normalized by loop size and transmitter moment and may be used to calculate the sheet conductance simply by matching normalized field data to the curve and reading the normalized time coordinate.

The horizontal gradients of the vertical field for the central-loop profiles may be used in much the same manner as the horizontal fields if several conditions are met. First the gradients must be measured normal to a two-dimensional contact and secondly the stations must be spaced 0.5 to 1.0 loop apart for an accurate calculation of the gradient. In many cases these are reasonable conditions; for such data some of the techniques described above can be applied.

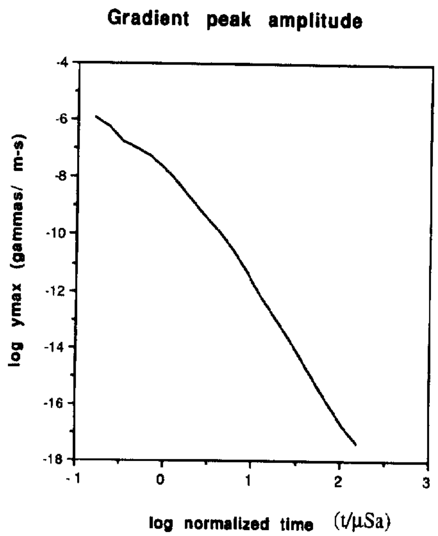

Figure 3 Normalized horizontal gradient peak amplitude for a truncated sheet.

Field Example

An excellent case history paper by Irvine and Staltari (1984) is used to illustrate the central-loop horizontal gradient. Fixed-loop EM collected over the Brittania prospect in Queensland, Australia, were initially interpreted as a vertically dipping sheet. After a series of fruitless drillholes and additional surface EM and resistivity surveys, however, it was discovered that a surface contact was the main cause of the anomaly. In their conclusions Irvine and Staltari (1984) suggested that in areas of conductive surface layers TDEM prospecting should include coincident loop profiles and fixed-loop profiles made from several loop positions. They state that from this combination of field surveys contact anomalies can readily be distinguished from other anomalies of interest.

Irvine and Staltari (1984) stated that of all the surveys conducted at Brittania, the coincident loop data was the most diagnostic of the contact effect; they also stated, however, that this is not the preferred method for ore prospecting. As shown in Spies and Parker, (1984) central-loop or coincident-loop profiles show a simple level adjustment across a contact so the edge effect is not so ambiguous as it is for the fixed-loop system. One problem is that it is not clear from the coincident loop profiles where the edge is nor is it obvious what the conductance or conductivity contrast is for the truncated layer. By examining the horizontal gradient of the vertical field, however, this information may be easily obtained.

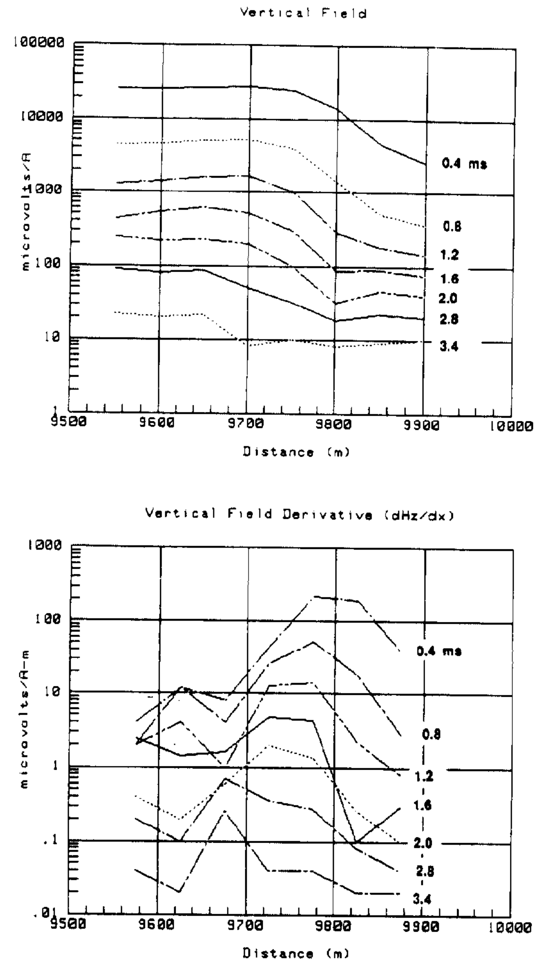

Figure 4 Coincident loop and horizontal gradient time profiles over line A-A' at the Brittania prospect (after Irvine and Staltari, 1984).

We plot the coincident loop data and its horizontal gradient for profile A-A' from Irvine and Staltari (1984) in Figure 4. The gradient data were computed from the coincident loop fields using the forward differencing scheme described earlier. While the coincident loop profiles show a simple field level change (which is characteristic of a surface contact) the gradient profiles form a series of peaks that migrate inwards from the contact at later and later times. We showed that the conductance of the surface layer may be obtained by plotting the location of the peak against the peak time. The slope of this plot is the velocity of the peak and for a truncated sheet this is a constant given by equation 1.

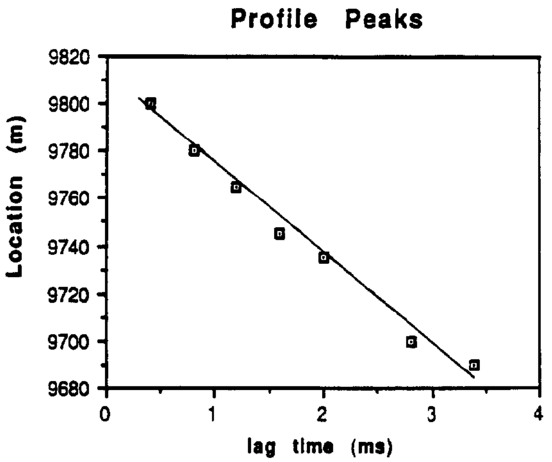

Figure 5 Location of the horizontal gradient profile peaks plotted against lag time for the Brittania data.

We plot the peak location against peak time for the Brittania horizontal gradient profiles in Figure 5; The slope of the plot is linear suggesting a constant velocity equal to 35,000 m/s. Applying this to equation (3) we obtain a value of S=9.1 Siemens, which is in close agreement with the value calculated from previous Schlumberger resistivity and other EM surveys. The location of the edge may be roughly obtained by extrapolating the curve in Figure 5 to zero lag time. This occurs near station 9825 which is also in accord with the location obtained from the fixed-loop EM data and Schlumberger resistivity soundings (Irvine and Staltari, 1984).

We showed above that the peak amplitudes of the horizontal gradient profiles are useful in determining the conductance of the layers forming the contact. Using the peak amplitudes of the horizontal gradient profile, shown in Figure 4, we can find the conductance on the more conductive side of the edge by matching this data to the normalized plot given in Figure 3. For example the peak amplitude at 2.0 ms is equal to 3.0 microvolts. Dividing by the loop area (10,000 sq. m)the normalized amplitude is 0.3 nano volts.

This voltage can be matched to Figure 3 to obtain a normalized time of 2.0. The conductance may be obtained by solving the time normalization equation for S, that is

$$S = \frac{t}{\mu_0 t_n a}$$

From the above equation where a=56m we calculate S=9.1 Siemens. This value is also in excellent agreement with the conductance estimates given above.

Conclusions

In this short paper we have shown that the horizontal gradient of the central-loop vertical field can be an effective tool in resolving geological inhomogenieties. For a truncated sheet the form of the anomaly is simple and the analysis straightforward, this might also be the case for other types of anomalous bodies. Because these gradients may be easily calculated for a large amount of existing TDEM data we expect that analysing these data would be a useful undertaking.

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